Fluidic Noise Shield

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Abstract

We are introducing a new “smart material” for acoustical applications, i.e., a material for active control of sound. Smart materials incorporate into their structure the sensing, actuation and control functions of an active-control system. The new concept makes use of fluidics for all three of these functions. Because of this there is no need for transduction, and the system operates entirely in the fluid domain without moving parts or electrical input.

A short background on some principles in fluidics is given before the new concept is described. Then the application of this technology to airplane interior trim is introduced. Analysis and experiments in progress on the NASA program are described.

Introduction

The pressure fluctuations that we perceive as sound are small modulations of a much larger steady, ambient pressure. For example, in air at normal atmospheric pressure, a very loud sound, with a sound pressure level of L_p= 100 dB ($p_{ref} = 20\mu Pa$) is only a modulation of about $p_s = 2Pa$ above an ambient pressure of about $10^5 Pa$.

$$L_p = 10 Log\left(\frac{\left(p_s^2\right)_{ave}}{p_{ref}^2}\right)$$

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Figure 1 diagrams the approximate threshold of hearing for young people, age 18-25.
Sound propagates as a longitudinal wave motion, which involves an interaction between the compressibility of the air and its inertia, at a wave velocity in air of about 340 m/s. This is slower than the speed of electromagnetic propagation by a factor of about 10^6. The frequency range of audible sound is from about 20 Hz to 20 kHz, which gives a wavelength in air of between 17 m and 17 mm. This range of wavelengths corresponds to the High Frequency (HF) to the Ultra High Frequency (UHF), Ku-band, region of electromagnetic waves.

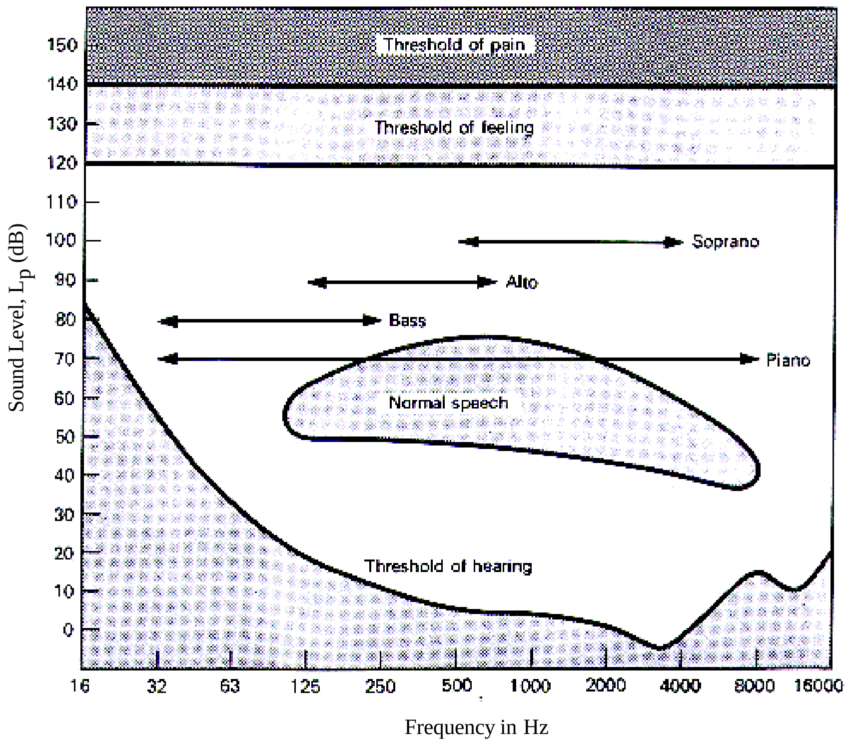


Figure 1 Approximate range of hearing, Ref [1]

Ranges of sound-pressure levels associated with different sources are indicated in
Table 1. The most important noise band for speech interference is from about 1-4 kHz. The ear is most sensitive from about 2-3 kHz. An approximate 13 dB amplitude above the noise floor is needed for perception of speech.

Level, dB (re 20 μ Pa)	Examples
140	Near jet engine (at 3 m)
130	Threshold of pain
120	Rock concert
110	Accelerating motorcycle (at 5 m)
100	Pneumatic hammer (at 2 m)
90	Noisy factory
80	Vacuum cleaner
70	Busy traffic
60	Two-person conversation
50	Quiet restaurant
40	Residential area at night
30	Empty movie house
20	Rustling of leaves
10	Human breathing (at 3 m)
0	Hearing threshold for person with acute hearing

Table 1 Examples of sound levels and given sources, Ref [2]

Passive methods for controlling unwanted sound and vibrations include insulation, silencers, vibration mounts, damping treatments, absorptive treatments and mufflers. Passive techniques work best at middle and high frequencies. The size and mass of passive treatment usually depends upon acoustic wavelength, making them thicker and more massive for lower frequencies. For lower frequencies, adaptive or active structural-acoustic control and active noise cancellation may be used with less weight and size than passive treatments. Adaptive and active structural-acoustic control are used to change the impedance of sound propagation from structure to the occupied space. Tonal sources such as turboprop engines are treated in industry through phase cancellation.

Active noise cancellation may treat a small space around the occupant's ears with active earphones or the inside of an automobile or air vehicle with speakers. The practical application of this technology can be limited however, to lower frequencies and spatial extent.

Active Noise Cancellation

Active control of sound results from destructive interference between the sound field of an original acoustic source and that from a controllable array of secondary acoustic sources. The important property of sound waves is that they propagate linearly. This makes active noise control possible. The field is the superposition of all individual contributing sources. Through destructive interference, an unwanted acoustic source is silenced with a controlled secondary source of equal magnitude and opposite phase. The destructive interference requires spatial and temporal matching between the original and secondary sources over the entire design volume. The spatial matching requirement leads to an upper frequency of applicability of active control.

Active noise cancellation is most easily applied to a spatially simple low-frequency sound field such as a sound wave in a duct; a one-dimensional problem. The German physicist, Paul Lueg, first published the principles of active noise control in a 1934 patent. Figure 2 is produced from the original patent and illustrates the methodology of active noise control in a duct. Diagram 1 shows a microphone M used to measure the offending sinusoidal sound wave S_1 produced by source A. The electrical output of the microphone passes through a controller V to drive a secondary acoustic source L. The secondary source generates the anti-phase acoustic wave S_2. Diagram 3 shows the cancellation of non-sinusoidal sound waves. Diagrams 2 and 4 show three dimensional active noise cancellation. The sound field from source A is cancelled with microphone M, Controller V, and Secondary Source L.

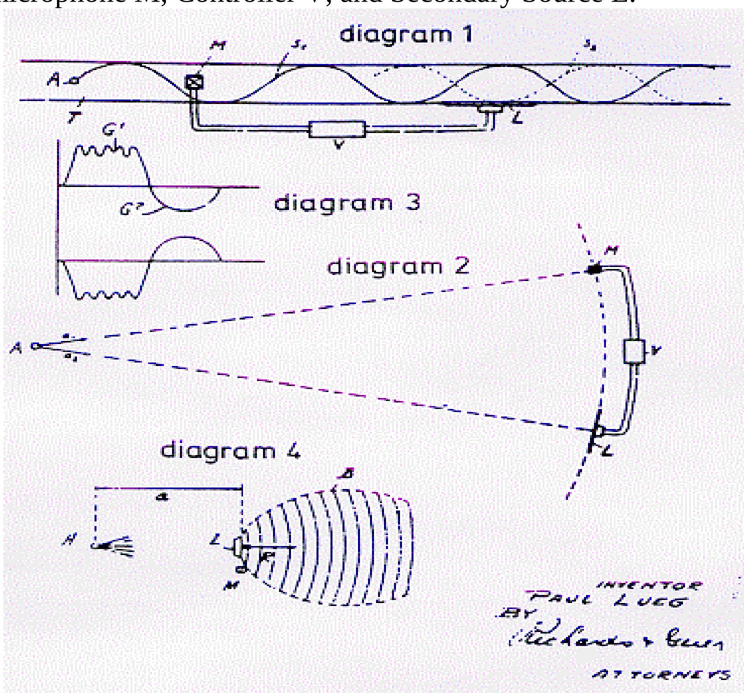


Figure 2 Original active noise cancellation patent, Ref [3]

Airplane Cabin Noise

Boeing installed and flight-tested an active noise cancellation system on the DeHavilland Dash 300, 50 passenger aircraft in August 1989. The Boeing design had 16 microphones and eight speakers. An illustration of such a system is shown in figure 3. The control system had an approximate 10 Hz updating frequency to manage the changing temporal and spatial sound field. The system demonstrated 15-18 dB reduction for the first harmonic, 10 dB reduction for the second harmonic and 5 dB reduction for the third harmonic. Boeing designed and built the controller for this system. The controller operated in the frequency domain, solved for 16 harmonics using a least squares matrix inversion and synthesized the loudspeaker wave through superposition of each harmonic.

Cabin room modes are damped (with a typical Q of about 5). The number of room modes rises in proportion to the cube of the excitation frequency. The Q is the ratio of peak power angular excitation frequency to the system response angular frequency band which encompasses on half of the excitation power. This is a measure of tonal response to a source excitation.

$$Q_n = \frac{\omega_n^0}{2\Delta\omega_{3dB}} = \frac{\frac{n\pi c}{\lambda}}{2\Delta\omega_{3dB}}$$

As the excitation source frequency is increased, the number of secondary sources must be dramatically increased in order to smooth out spectral in-phase wave superposition of the primary and secondary sources. This places a practical limit on the use of mechanical/electrical microphone/speaker systems to frequency treatment of about 200-300 Hz.

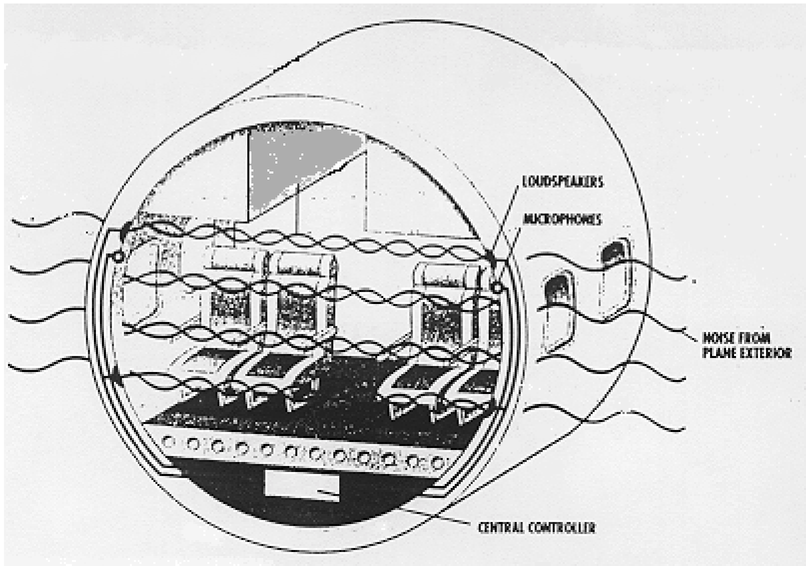


Figure 3 Aircraft with active noise control

Distributed Active Systems

As few as 20-40 loudspeakers on a propeller airplane may be used to treat engine noise because the frequency is low and the excitation concentrated. In contrast, another common problem for aircraft is boundary layer noise. Boundary layer noise is broad band ranging from about 1 kHz to 4 kHz. The highest frequencies occur toward the front of the fuselage and decrease with station position as the boundary layer thickness grows to approximately 1 ft. toward the aft end of commercial or transport aircraft. This causes speech interference problems. There are two difficulties however, which conventionally leads to the use of absorbing materials in lieu of active systems. As the wavelength shortens, it becomes more difficult for the active system controller to measure the wavefront and respond rapidly enough. Secondly, greater numbers of sensors and actuators are required to treat the design volume at higher frequencies. These problems are compounded with increasing field space control.

The required number of actuators for boundary layer noise reduction as a function of the upper frequency limit of required noise reduction for several Boeing vehicles is shown in figure 4. Any individual actuator must be light and inexpensive because of the large numbers required. Further, transduction back and forth between pressure signals in the air and electrical signals must be avoided at these frequencies.

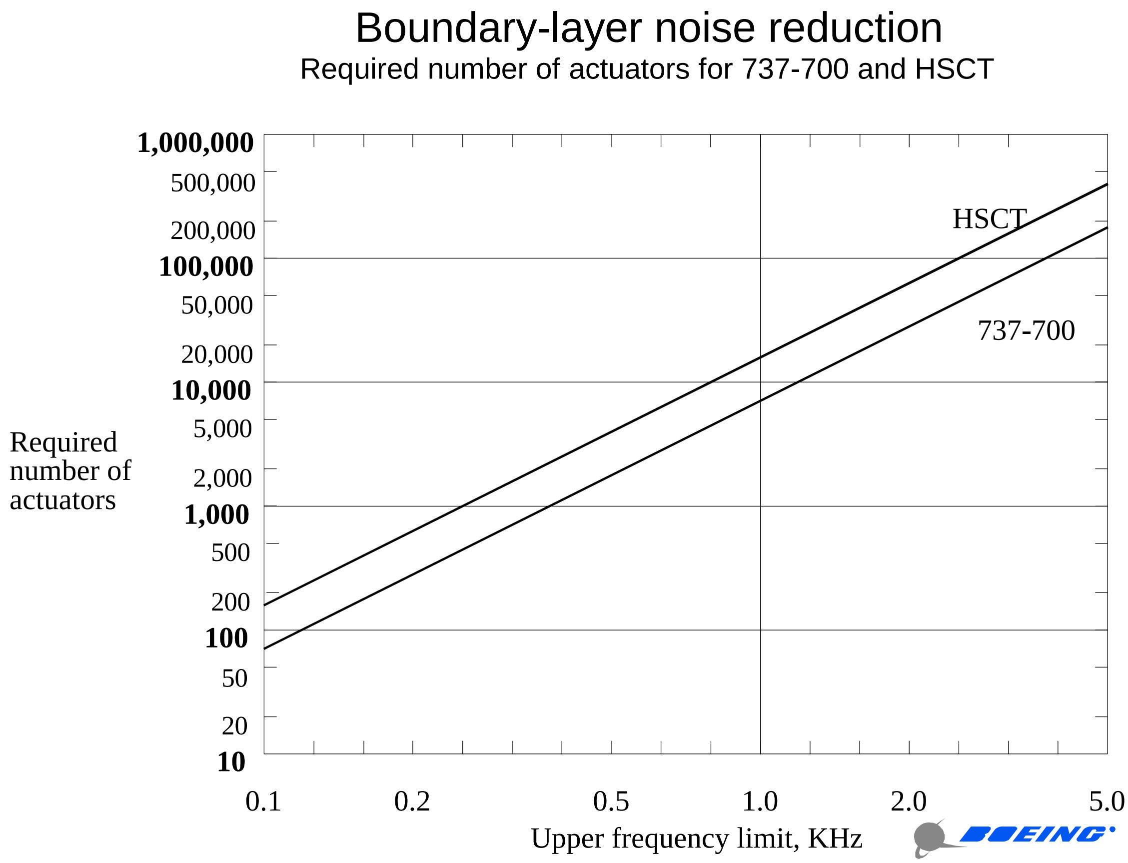


Figure 4 Actuator requirements vs. control frequency, Ref [4]

The basic component of fluidic circuits is the proportional amplifier.   A schematic of the proportional amplifier is shown in figure 5. What is shown here should be seen as a cutout in a thin sheet of flat material and covered on top and bottom by other thin sheets. Holes are cut out in the top and bottom sheets to allow air to be supplied or led away from the pattern. The supply port pressure drives supply air towards a splitter. A small pressure differential is applied across the control ports, the jet deflects and one of the output ports receives a greater amount of flow, and therefore a greater pressure rise. The output port pressure differential is proportional to the control-port pressure differential, hence the name "proportional amplifier." The "microphone" air pressure controls the pressure at the control ports.

Fluid velocities can reach high subsonic levels in these fluidic components. The jet travels through a vented, ambient-pressure area. The longer the vented area the greater the amplification. Longer vented area also increases the time delay between application of the control pressure and sensing of the amplified pressure at the output. Time delays limit the frequency range of active control systems.

The fluidic amplifiers can be cascaded just like electronic amplifiers. This is important since the amplification per stage is a moderate five to eight times the control port pressure. The cascading also adds to the total time delay through the circuit.

Note that there is a steady flow through the device. When we later apply this device to acoustics it is this steady flow that we modulate. The fluidic proportional amplifier provides required noise control output air volumes more efficiently than mechanical/electrical transducers.

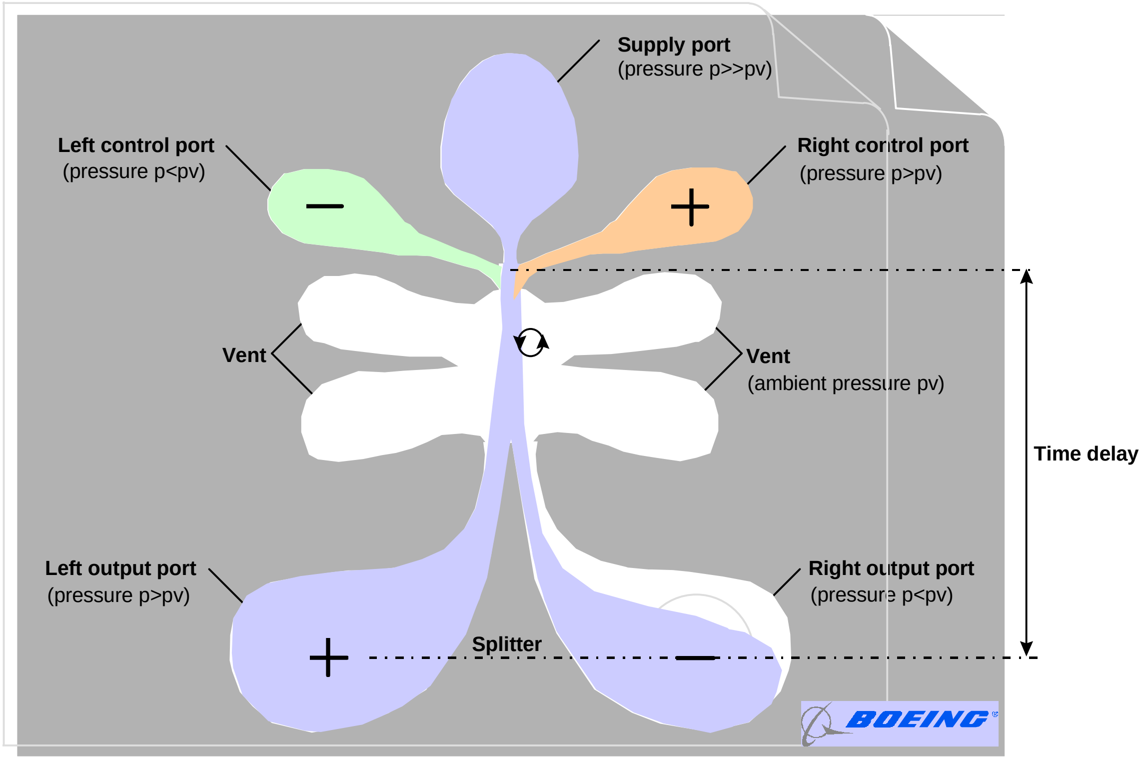


Figure 5 Fluidic acoustic stack proportional amplifier principle, Ref [4]

Figure 6 shows a laminar jet in an experimental fluidic amplifier. For low self-noise laminar flow is preferred, particularly in the first stages of a fluidic amplifier. For the final stages supersonic, turbulent jets could possibly be used for greater volume flow and lower time delays.

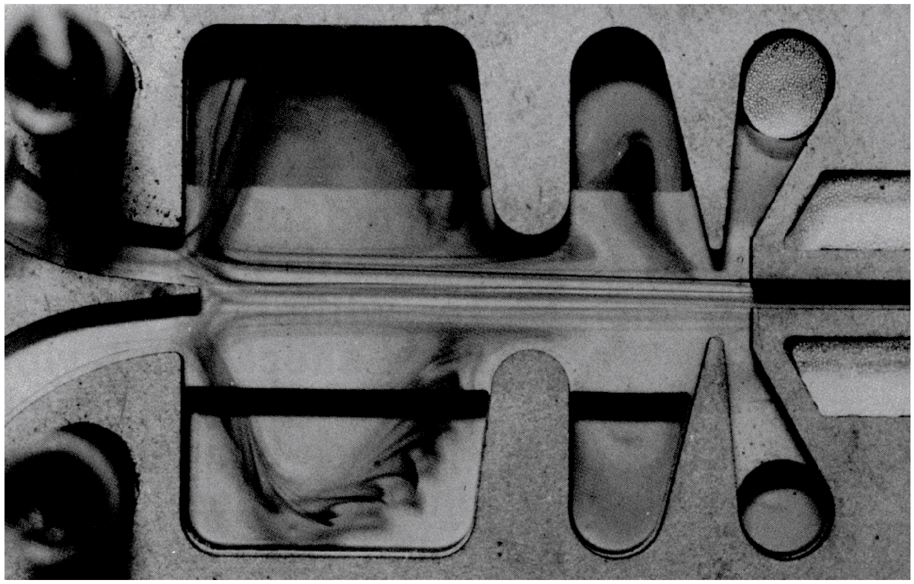


Figure 6 Laminar flow through a fluidic amplifier, Ref [4]

A simplified, exploded view of the fluidic circuit build-up is illustrated in figure 7. The different amplifier stages are separated by "transfers" which connect the stages.

The individual circuits in the array are arranged in order to obtain favorable acoustic impedance. One hole in the faceplate is labeled "microphone" and is connected to a control port of one of the amplifier stages, labeled 6 in the picture. An incoming wave or an overpressure created by the vibrating wall would be amplified through the three amplifier stages and emerge as a negative pulse, i.e. a reduction in the steady flow, through the hole labeled "loudspeaker."

The surface could be said to "swallow" the pressure wave and would therefore have lower impedance than a hard wall. The noteworthy thing is that this property persists down to the lowest frequencies. At some higher frequency the time delay in the circuit will be large enough to make the loudspeaker play in the same phase as the input and therefore cause an amplification of the sound. In order to prevent this, acoustical filters have to be inserted in the circuit in order to maintain stability.

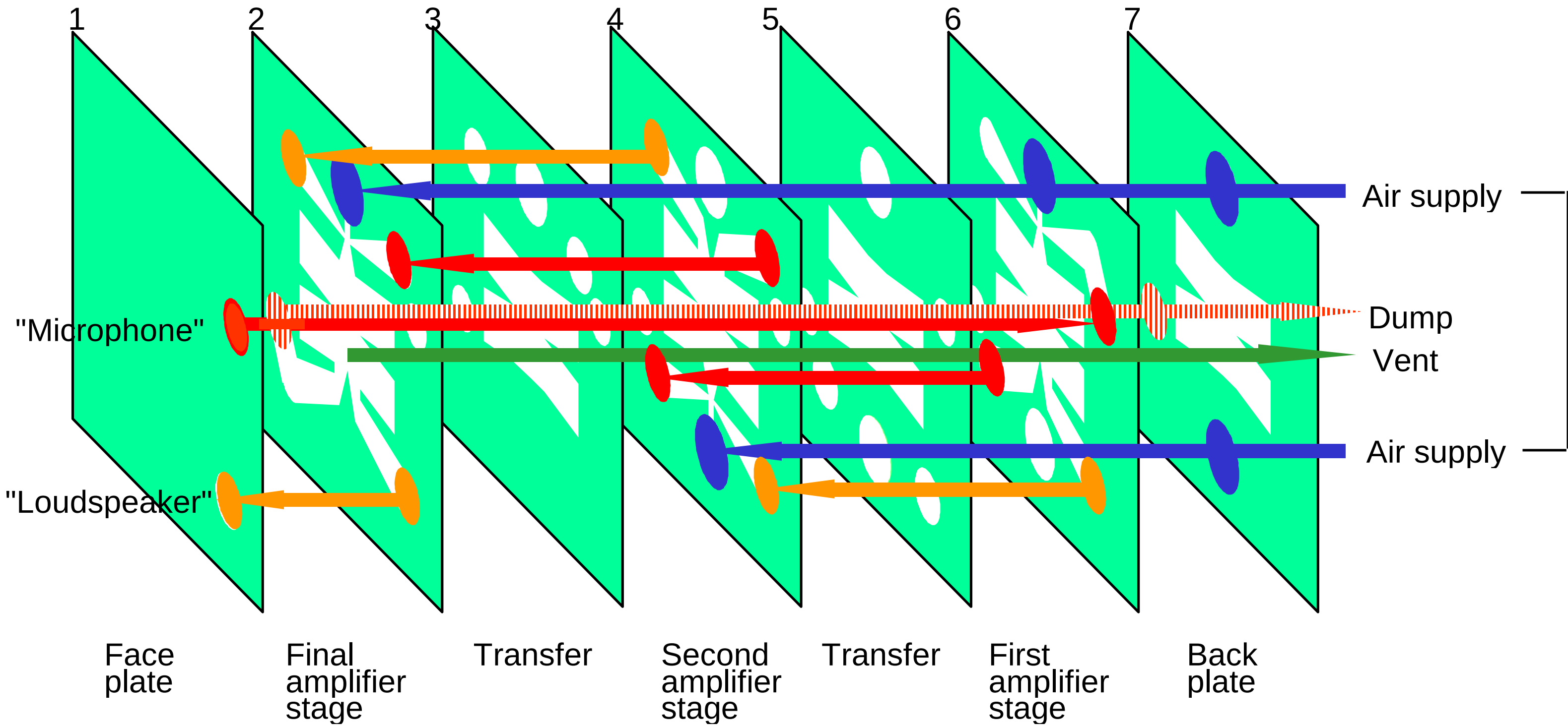


Figure 7 Fluidic acoustic stack, Ref [4]

Examples of the patterns that would have to be formed are shown in figure 8 based on designs in the 1.25 and 0.75-inch formats. These are typical components used in applications for Boeing, such as the backup hydraulic system speed control. In addition to the fluidic amplifiers themselves, the components include resistances in the form of capillaries or orifices, capacitances in the form of volumes, and ”transfers” which are simply connections between components.

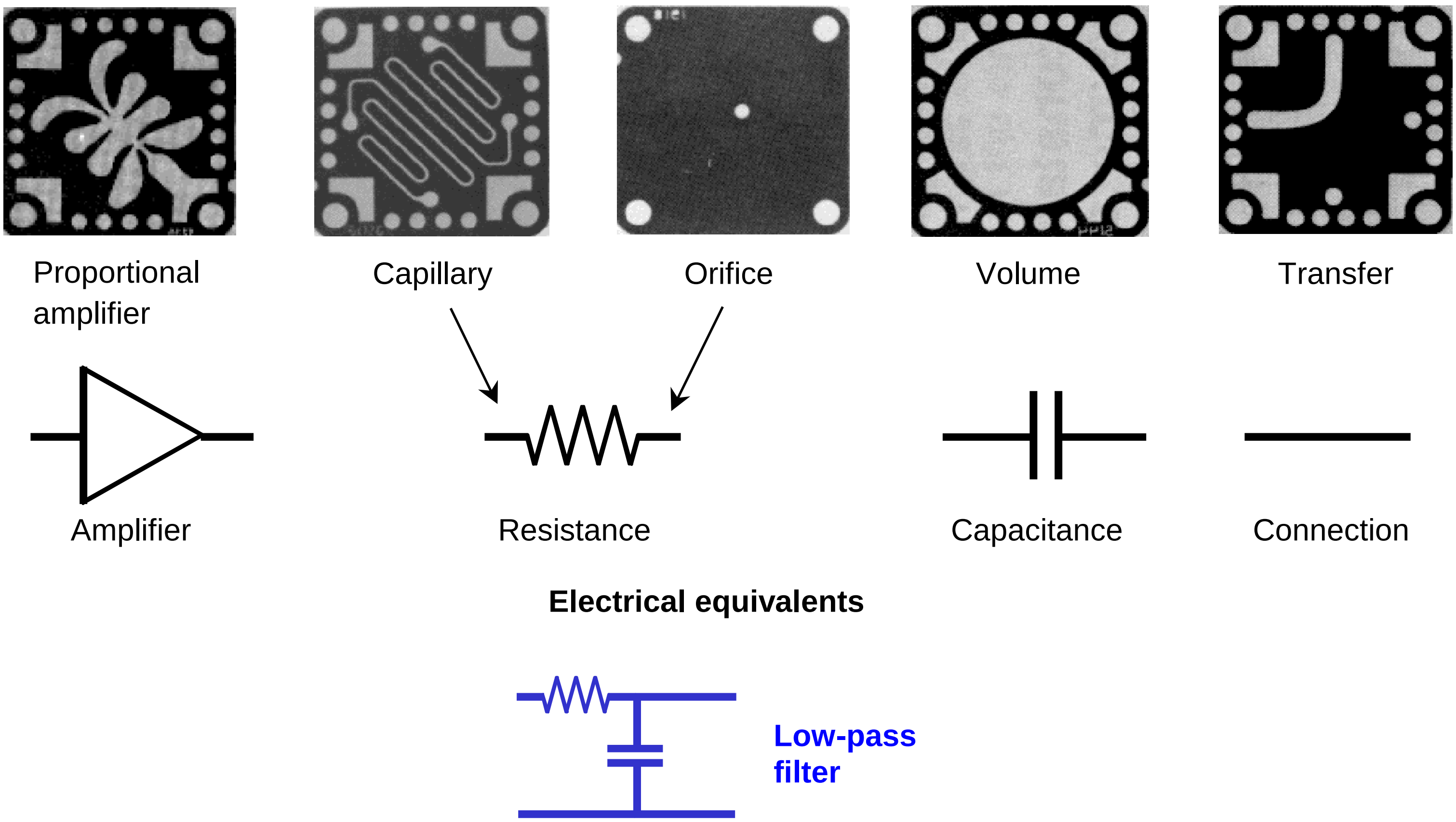


Figure 8 Equivalent fluidic and electrical elements, Ref [4]

The fluidic noise shield under development at Boeing uses a fluidic acoustic stack design. This system uses compressed environmental systems air as a power source and consists of layers of patterned sheets. Each sheet contains many pre-stamped patterns. These patterns perform noise control operations. Noise control occurs due to air volume displacement from controlled air mass emissions. A layer from the fluidic stack is shown in figure 9. The two-dimensional array of amplifiers is arranged with other layers of fluidic components in a stack to form a three-dimensional system of "acoustical wallpaper."

Depending on the application, the impedance of this array could be made optimal for absorption in a room or a muffler or made to minimize the radiation from a vibrating wall. An absorbing wall should have an impedance in the range 1-2 ρc while a vibrating wall should have as low an impedance as possible. A muffler lining should have impedance with both real and imaginary parts, both proportional to frequency. This is difficult to accomplish even over a relatively small frequency range, but the fluidic concept makes low impedance at low frequencies possible.

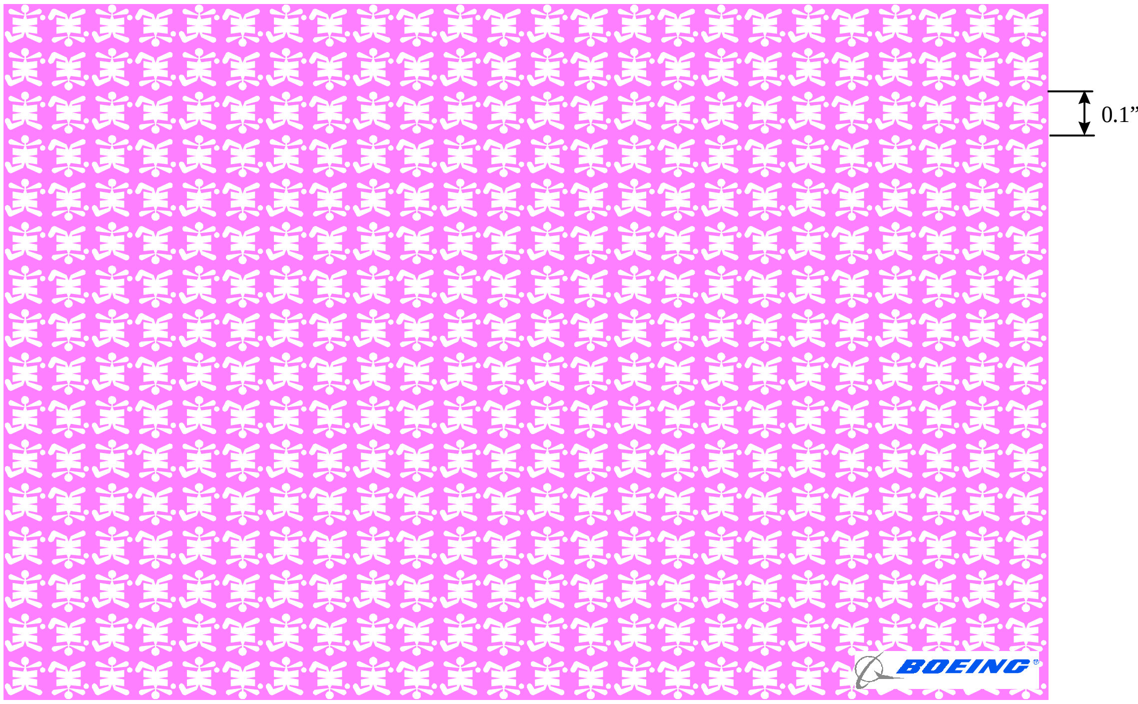


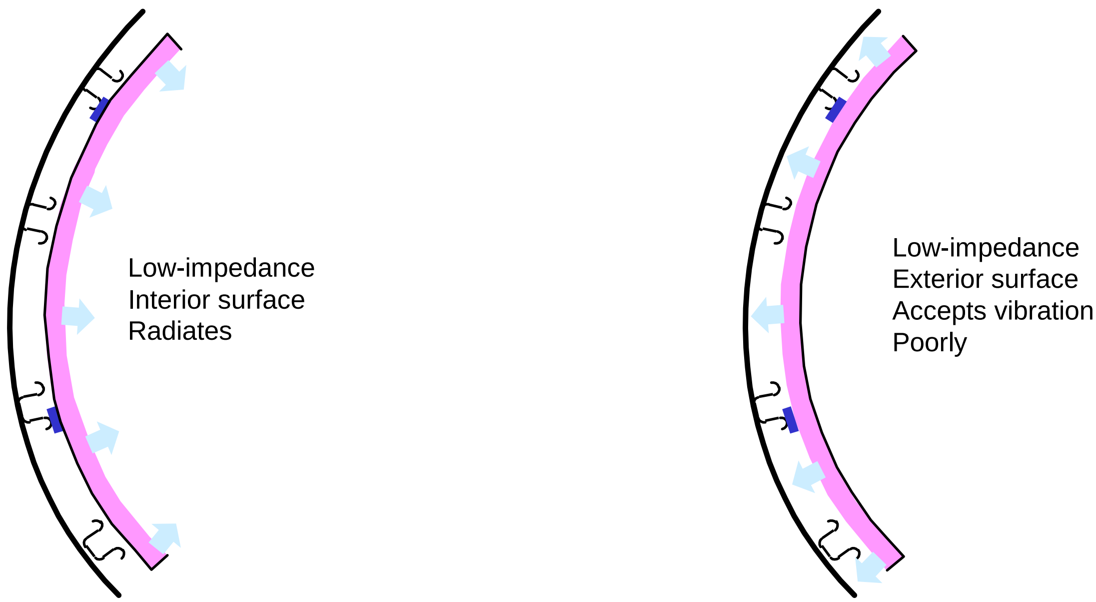
Figure 9 One layer of stack from fluidic wallpaper, Ref [4]

Airplane Cabin Fluidic Noise Shield Application

Trim-panel applications are shown in figure 10. The active side of the panel could face inward or outward, with arguments pro and con in both cases. The left configuration shows a panel with the active side toward the passengers. In this case it doesn’t matter what causes the vibration, the panel reduces noise by simply radiating inefficiently. It also provides a low-speed air-conditioning flow. The panel has steady airflow, which is reduced when the panel moves inward and is increased when it recedes. A disadvantage is that the surface is porous.

This disadvantage is removed if the panel is turned around so that the active surface is facing the primary structure. This also allows any decorative treatment of the trim surface. The panel reduces noise by not accepting motion from the acoustically compressed air in the space between the trim and the primary structure. This is the same noise reduction as in the previous case. But the motion of the trim caused by the attachment points is not reduced at all, and this limits the noise reduction above about 1000 Hz. The panel airflow would not provide direct air conditioning but might be led to air-conditioning outlets or be used for other purposes, e.g. primary-structure cooling on the HSCT.

Interior side active **Exterior side active**



Advantages

Interior side active:

- Greatest acoustic efficiency
- Provides diffuse air conditioning

Exterior side active:

- Non-porous interior surface
- Any surface material may be used
- Might provide cooling air on HSCT

Disadvantages

Interior side active:

- Porous interior surface

Exterior side active:

- Attachment points provide noise flanking path
- No automatic air-conditioning

Figure 10 Alternate trim applications, Ref [4]

Fluidic Noise Shield Performance

Figure 11 shows the performance of a vibrating wall with an active fluidic noise shield consisting of 1.25- inch vs. 0.1-inch unit sizes as compared to a vibrating hard wall. The large noise reduction at low frequencies is worth noting.

The amplification of the sound at higher frequencies should be noted. It is an unavoidable feature of all active-control systems, feed-forward or feedback, but can be traded in magnitude against the bandwidth and amount of attenuation in the stop band.

It should be pointed out that the size of the amplifiers in this particular prediction was AlliedSignal's standard 1.25-inch square module. Miniaturization of the amplifiers will increase the frequency bandwidth in inverse proportion to the size, as shown in the blue curve representing a projection to 0.1-inch unit size.

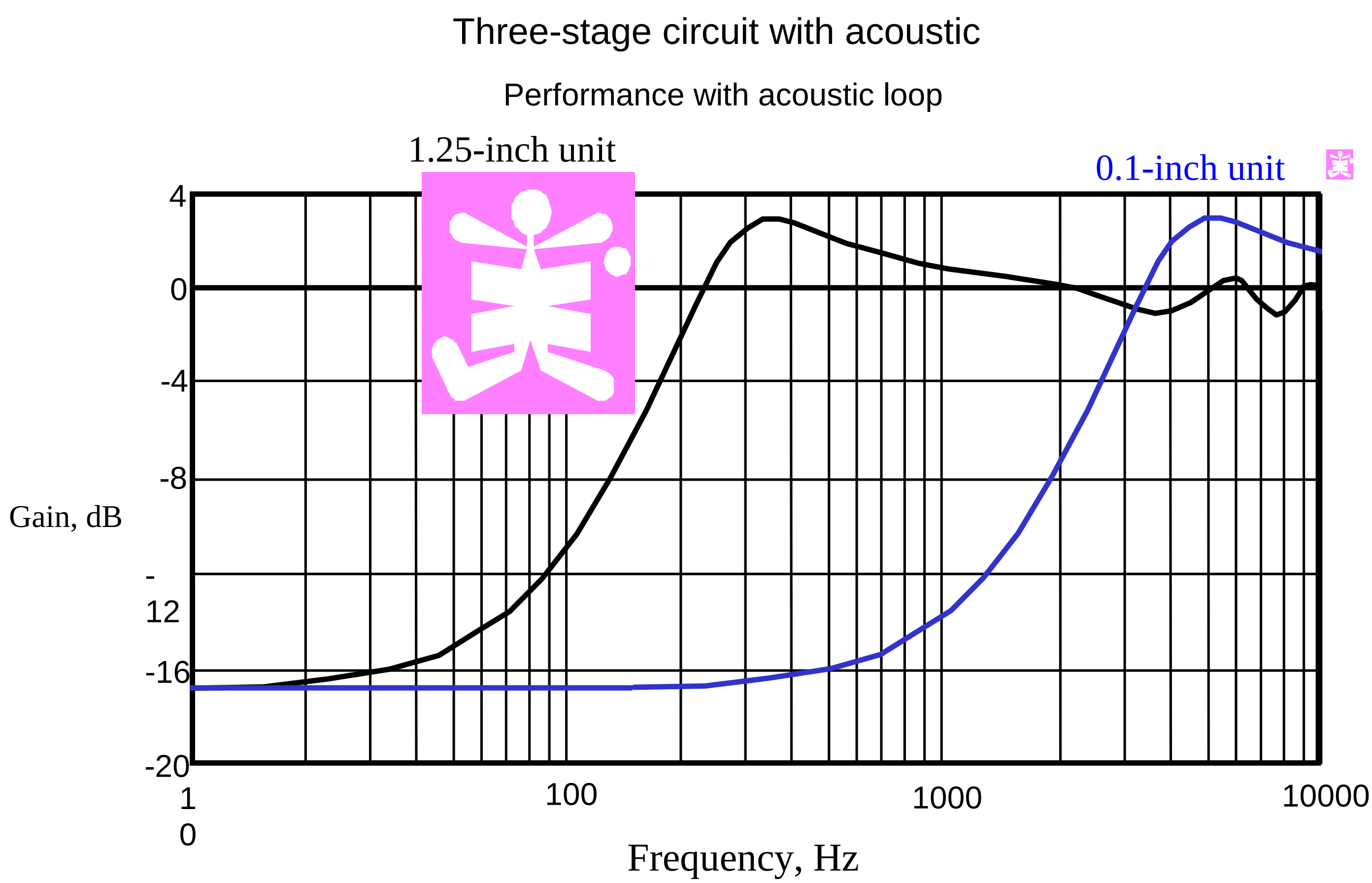


Figure 11 Fluidic noise shield performance prediction, Ref [4]

Conclusion

The potential for this new technology leads us to a vision.

There is a need to increase the upper frequency limit of active noise suppression systems into the kHz region for noise sources such as boundary layer noise. Boeing's fluidic noise shield promises to meet this need offering a low cost, low weight design which eliminates the need for mechanical/electrical transduction by operating entirely in the fluidic domain. Our approach makes it possible to create very large arrays of sensors and actuators, something which to date has been a stumbling block in active-control systems for distributed noise sources, such as the boundary layer of an aircraft.

The fact that there is a steady flow through the fluidic elements makes it natural to combine air conditioning with fluidic noise control. The steady flow necessary for noise control in an airplane cabin would amount to a velocity of only a few centimeters per second and would therefore provide dispersed, draft-free ventilation.

We have seen how thin low-impedance linings have potential for low-frequency noise reductions in several applications. One application is low-frequency mufflers of small volume and another might be a treatment behind the wedges of an anechoic chamber to extend the performance to lower frequencies. One could foresee the use of thermoplastic films with fluidic patterns fused into planar wallpaper arrays or rolled up into cylindrical muffler linings.

Low-cost manufacturing methods need to be developed, to be able to use this technology on a large scale. Future work would entail development of manufacturing methods for the trim material as well as design of complete trim systems.

References

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